

Library of SM and anomalous  $WW\gamma$  couplings for the  
 $e^+e^- \rightarrow f\bar{f}n\gamma$  Monte Carlo programs**A. Jacholkowska***Laboratoire de l'Accélérateur Lineaire, CNRS-IN2P3, 914050 Orsay, France***J. Kalinowski***Instytut Fizyki Teoretycznej, Hoża 69, 00681 Warszawa, Poland*

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A brief description of the library of the Standard Model and anomalous  $WW\gamma$  coupling contribution to the matrix element for  $e^+e^- \rightarrow \nu\bar{\nu}n\gamma$  process is given. It can be used with any Monte Carlo program for  $e^+e^- \rightarrow f\bar{f}n\gamma$  processes. A working example of the application for the KORALZ version 4.04 is also provided.

*To be submitted to Computer Physics Communications***CERN-TH/99-120****IFT/99-06****May 1999**


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<sup>†</sup> Work supported in part by Polish Government grants KBN 2P03B08414, KBN 2P03B14715, KBN 2P03B03014 (JK), Maria Skłodowska-Curie Joint Fund II PAA/DOE-97-316, and Polish-French Collaboration within IN2P3.

# 1 Introduction

The  $\nu\bar{\nu}\gamma$  production in  $e^+e^-$  collisions is of great interest, as it is sensitive to the triple gauge boson coupling  $WW\gamma$  of the Standard Model. Its precise measurement will not serve only as a stringent test of the SM, but may reveal (or constrain) anomalous gauge couplings. The events with photon(s) plus missing energy might originate also from other mechanisms, signalling new physics beyond the Standard Model. For example, such final states can be produced in both gravity- and gauge-mediated supersymmetric models or low-scale gravity. The missing energy in these events is caused by weakly interacting supersymmetric particles, such as gravitinos, neutralinos and/or sneutrinos [1], or gravitons [2]. In all such cases the Standard Model  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  events are irreducible background and reliable theoretical predictions for them are therefore necessary.

With the sensitivity afforded by the LEP experiments [3, 4], and expected at future  $e^+e^-$  colliders [5], the photon(s) plus missing energy events provide an opportunity to search for new physics phenomena. Any meaningful interpretation of the experimental data requires a Monte Carlo simulation in which Standard Model predictions may be augmented by the contributions from possible anomalous couplings.

Since the LEP collaborations are entering their final years of operation, now is a good time to document the programs that have actually been used in the data analyses at LEP. In the present paper we document the library for the calculation of the effects of the  $WW\gamma$  interaction for the  $e^+e^- \rightarrow \nu\bar{\nu}n\gamma$  process within the Standard Model as well as from the anomalous couplings. It is based on the work of [6] and the description of the physical content of the program interface and discussion of its uncertainties can be found in [7]. For an alternative implementation of the  $WW\gamma$  vertex, see [8].

In principle our library can be combined with any  $e^+e^- \rightarrow f\bar{f}n\gamma$  generator, but in the present paper we will use an interface to KORALZ version 4.04, described in [10, 11], as a working example. That is the reason why the fortran code of the library will be archived together with the KORALZ tree of subdirectories [11]. Let us note that, in future, KORALZ will be replaced by a new program, KK2f [12], which is based on a more powerful exponentiation at the spin amplitude level and in which the library will also be easy to implement.

Version 4.04 of the KORALZ Monte Carlo program can be used to simulate  $e^+e^- \rightarrow f\bar{f}n\gamma$ , ( $f = \mu, \tau, u, d, c, s, b, \nu$ ) processes up to the LEP2 energy range, including YFS exclusive exponentiation of initial- and final-state bremsstrahlung and, optionally, the effects of various anomalous couplings. In the case of the LEP2 centre-of-mass energies and if  $f = \nu$ , the present library can be used for that purpose.

## 2 Calculation of anomalous couplings

To evaluate the effects of anomalous  $WW\gamma$ , a tree-level calculation of the squared matrix element for the process  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  has been carried out [6]. It includes the effects of the anomalous C- and P-conserving<sup>1</sup> contributions parametrized with the help of the

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<sup>1</sup>For a recent phenomenological analysis of CP-violating couplings in  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ , see [9].

couplings  $\Delta\kappa_\gamma$ ,  $\lambda_\gamma$  (in what follows we will suppress the subscript  $\gamma$ ). The library is formed on this basis. When activated, it uses the 4-momenta of the neutrinos and the photon provided by the host program to compute a weight,  $w$ , for each event according to

$$w = \frac{|\mathcal{M}_{\text{SM}}^{WW\gamma \text{ excl.}} + \mathcal{M}_{\text{SM}}^{WW\gamma} + \mathcal{M}_{\text{ano}}^{WW\gamma}|^2}{|\mathcal{M}_{\text{SM}}^{WW\gamma \text{ excl.}}|^2}. \quad (1)$$

$\mathcal{M}_{\text{ano}}^{WW\gamma}$  is the matrix element due to the anomalous  $\Delta\kappa \neq 0$ ,  $\lambda \neq 0$  couplings, the  $\mathcal{M}_{\text{SM}}^{WW\gamma}$  is the matrix element due to the SM  $WW\gamma$  interaction and  $\mathcal{M}_{\text{SM}}^{WW\gamma \text{ excl.}}$  represents the remaining part of the SM matrix element for the  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  process<sup>2</sup>. Note that because of the above separation, even for the Standard Model  $WW\gamma$  interaction, the use of the library is necessary to calculate the weight  $w$ .

As the calculation of ref. [6] is performed at  $\mathcal{O}(\alpha)$ , the case of multiple bremsstrahlung requires a special treatment. In this case, a reduction procedure is first applied in which all photons except the one with the highest- $p_T$  are incorporated into the 4-momenta of effective beams. In the second step, the 4-momenta of the highest  $p_T$  photon, the effective beams and neutrinos are then used to compute the weight. Cross-checks of the calculation as well as checks of the validity of the reduction procedure are described in [7]. The results of the calculation have been used in the measurement of the  $WW\gamma$  coupling described in [3].

### 3 Flags to control anomalous couplings in KORALZ

The calculation of weights for anomalous couplings is activated by setting the card `IFKALIN=1`. This is transmitted from the main program via the KORALZ input parameter `NPAR(15)`. Additional input parameters are set in the routine `kzphynew(XPAR,NPAR)`, although there are currently no connections to the KORALZ matrix input parameters `XPAR` and `NPAR`<sup>3</sup>. Table 1 summarizes the functions of these input parameters.

More input parameters are initialized in the subroutine `anomini`, which is placed in the file `gengface.f` and subroutine `initialize` of the file `geng.f`. Both files are placed in the directory `korz_new/nunulib`.

In order to provide the user with enough information to retrieve the  $w$  for a given event for any  $\Delta\kappa$ ,  $\lambda$ , we take advantage of the fact that, for each event, one may write the  $w$  as a quadratic function of the anomalous couplings, in terms of the results calculated for six numerically distinct combinations of the  $\Delta\kappa$ ,  $\lambda$  values as follows:

$$\begin{aligned} w(\Delta\kappa, \lambda) = & \left(1 - \left(\frac{\lambda}{\lambda_0}\right)^2 - \left(\frac{\Delta\kappa}{\Delta\kappa_0}\right)^2 + \frac{\lambda}{\lambda_0} \frac{\Delta\kappa}{\Delta\kappa_0}\right) w(0, 0) - \left(\frac{\Delta\kappa}{2\Delta\kappa_0} - \frac{1}{2} \left(\frac{\Delta\kappa}{\Delta\kappa_0}\right)^2\right) w(-\Delta\kappa_0, 0) \\ & + \left(\frac{\Delta\kappa}{2\Delta\kappa_0} + \frac{1}{2} \left(\frac{\Delta\kappa}{\Delta\kappa_0}\right)^2 - \frac{\lambda}{\lambda_0} \frac{\Delta\kappa}{\Delta\kappa_0}\right) w(\Delta\kappa_0, 0) - \left(\frac{\lambda}{2\lambda_0} - \frac{1}{2} \left(\frac{\lambda}{\lambda_0}\right)^2\right) w(0, -\lambda_0) \end{aligned}$$

<sup>2</sup>Note that such a separation is gauge-dependent and, if not treated carefully, could lead to meaningless results. See ref. [7] for details.

<sup>3</sup>In most uses of KORALZ, the numerical value of these parameters is irrelevant or defaults are sufficient. It is expected that the advanced user may like to change them, connecting directly the `kzphynew(XPAR,NPAR)` routine with her or his main program.

Parameter	Description	Default
IENRICH	Enrich spectrum of generated sample with hard-photon events IENRICH= 1/0 (on/off)	0
IRECSOFT	Generate <i>only</i> events with photon(s) if IRECSOFT= 1	0
EMINACT	Minimum sum of all photon energies required to calculate anomalous weights	17 GeV
EMAXACT	Maximum sum of all photon energies allowed to calculate anomalous weights	1000 GeV
PTACT	Minimum sum of all photon momenta transverse to the beam direction required to calculate anomalous weights	2 GeV

Table 1: Input parameters to control the calculation of weights for anomalous  $WW\gamma$  couplings.

$$+ \left( \frac{\lambda}{2\lambda_0} + \frac{1}{2} \left( \frac{\lambda}{\lambda_0} \right)^2 - \frac{\lambda}{\lambda_0} \frac{\Delta\kappa}{\Delta\kappa_0} \right) w(0, \lambda_0) + \frac{\lambda}{\lambda_0} \frac{\Delta\kappa}{\Delta\kappa_0} w(\Delta\kappa_0, \lambda_0). \quad (2)$$

When the calculation is completed, the six weights are stored in the common block `common/kalinout/ wtkal(6)`, with the assignments shown in Table 2. The user is then free to

Common block entry	Weight parameter
<code>wtkal(1)</code>	$w(0, 0)$
<code>wtkal(2)</code>	$w(-\Delta\kappa_0, 0)$
<code>wtakl(3)</code>	$w(\Delta\kappa_0, 0)$
<code>wtkal(4)</code>	$w(0, -\lambda_0)$
<code>wtkal(5)</code>	$w(0, \lambda_0)$
<code>wtkal(6)</code>	$w(\Delta\kappa_0, \lambda_0)$

Table 2: Correspondence between entries in `kalinout` common block entries and weight parameters of eq. 2.

calculate the  $w$  for whatever combination of  $\Delta\kappa$  and  $\lambda$  is desired. In our program we set  $\Delta\kappa_0 = 10$  and  $\lambda_0 = 10$ . If the `IENRICH` input parameter is set to 1 the generated sample will have more events with hard photons than predicted by the Standard Model. The appropriate compensating factor is included into the weights `wtkal`. It is thus always assured that e.g. the generated sample, if the weight `wtkal(1)` is used, represents the Standard Model predictions.

The code for a calculation of the weight  $w$  is placed in the directory `korz_new/nunulib` in the files `geng.f` and `gengface.f`.

## 4 Demonstration programs

The demonstration program `DEM03.f` for the run of KORALZ when our library is activated can be found in the directory `korz_new/february` and the output `DEM03.out` in the directory `korz_new/february/prod1`. The `DEM0.f` for the run of KORALZ with the Standard Model interactions only and its output `DEM0.out` are also included in the directories mentioned above. All these files as well as the library itself are archived together with KORALZ [11].

## Acknowledgements

One of us (ZW) thanks CERN Theory Division for support during the final work on the paper.

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